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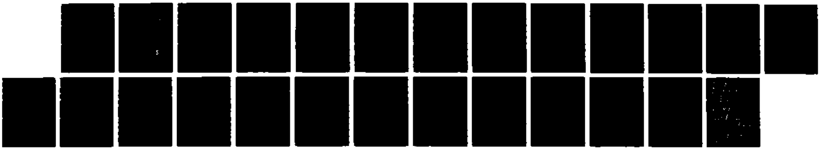

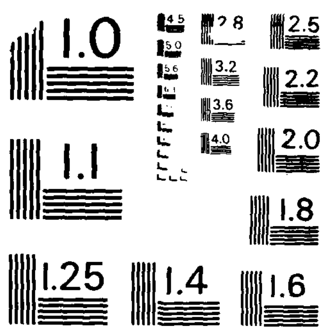

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SPACE-VARIANT OPTICAL SYSTEMS

Final Technical Report

on

AFOSR Grant 84-0382

(September 30, 1984 - September 30, 1987)

by

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November 1987

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 87-1860
6a. NAME OF PERFORMING ORGANIZATION Texas Tech University 6b. OFFICE SYMBOL (If applicable) EE Dept	7a. NAME OF MONITORING ORGANIZATION Air Force Office of Scientific Research
6c. ADDRESS (City, State and ZIP Code) Dept. of Electrical Engineering Lubbock, TX 79409-4439	7b. ADDRESS (City, State and ZIP Code) Building 410 Bolling AFB, DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR 8b. OFFICE SYMBOL (If applicable) AFOSR/NE	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR Grant 84-0382
8c. ADDRESS (City, State and ZIP Code) Bolling AFB DC 20332-6448	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO.: 61102F; PROJECT NO.: 2305; TASK NO.: B1; WORK UNIT NO.:

11. TITLE (Include Security Classification)
Space-Variant Optical Systems (unclassified)

12. PERSONAL AUTHOR(S)
Walkup, John F. and Krile, Thomas F.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Final	FROM 9/30/84 TO 9/30/87	1984, Nov. 30	21

16. SUPPLEMENTARY NOTATION
Final Technical Report

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Space-Variant Optical Processing Optical Computing; Optical signal processing Optical interconnection networks

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Analytical and experimental investigations of 1-D and 2-D space-variant optical processors have been conducted. Areas investigated have included: (1) measures of the degree of invariance of linear optical systems; (2) a real-time holographic CCD recording technique for preserving phase information; (3) a fast, highly parallel architecture for optical multiplication; and (4) a complete analytical and experimental investigation of the bilinear transform and its applications.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. C. Lee Giles	22b. TELEPHONE NUMBER (Include Area Code) 202-767-4931 22c. OFFICE SYMBOL AFOSR/NE

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE. UNCLASSIFIED

ABSTRACT

Analytical and experimental investigations of 1-D and 2-D space-variant optical processors have been conducted. Areas investigated have included: (1) measures of the degree of invariance of linear optical systems; (2) a real-time holographic CCD recording technique for preserving phase information; (3) a fast, highly parallel architecture for optical multiplication; and (4) a complete analytical and experimental investigation of the bilinear transform and its applications.

RESEARCH OBJECTIVES

During the period of the grant, from September 30, 1984 to September 30, 1987, the major research objectives have been to analytically and experimentally investigate the optical implementation of space-variant information processing operations. Both one-dimensional (1-D) and two-dimensional (2-D) signal processors have been studied. The major areas of investigation have been (1) investigation of an improved measure of the degree of invariance of a linear system and its application to piecewise isoplanatic space-variant systems; (2) a process for generalized real-time linear filtering of 1-D signals which incorporates a CCD-based recording technique for preserving phase information; (3) investigation of an all optical technique for multiplying binary numbers with a high degree of parallel processing; and (4) a complete analytical and experimental investigation of the bilinear transform and its widespread applications including programmable optical interconnections, triple product processors, 2-D optical crossbar networks, optical polynomial processors and window programmable image processors. Details of these investigations are provided in the following sections and in the referenced publications which have resulted from the research.

SUMMARY OF RESULTS

In consideration of the large number of journal publications, conference proceedings and the scientific report resulting from this research, we will briefly summarize the major results obtained in this section, with references made to the appropriate publications and report.

1. Measures of Invariance of Linear Systems

It has previously been shown by our group that, for bandlimited inputs, a space-variant linear system can be exactly characterized by knowledge of the sampled system point spread function and the corresponding sampled input.[1,2] Optical processors based on the sampling technique have, to date, encountered rather severe limitations in terms of input resolution, dynamic range and space-bandwidth product requirements for the system components. The implementation of space-variant optical processors based on the piecewise isoplanatic approximation (PIA) should alleviate some or all of these restrictions, since the PIA uses "coarse" sampling. The approximation employed divides the linear system input plane into isoplanatic patches to which corresponding point spread functions are assigned. The resulting PIA system output is an approximate representation of the true system output.

During this funding period, a new measure of the degree of invariance was developed as a tool to classify linear systems.[3,4,5] This new measure seems to predict the relationships between the true and PIA system outputs better than the classical Lohmann and Paris measure.[5,6] With the aid of the new measure, we showed how to find the optimal size of each isoplanatic patch in the input plane and the optimal corresponding impulse response in each patch. Finally the relationship of the variation bandwidth to the new measure of invariance was studied and found to support the validity of the new measure.

2. Real-time Holographic CCD Recording

This project investigated a technique for optically performing generalized coherent linear filtering of 1-D signals. A key element in the success of the processor is the use of a real-time holographic recording technique at the output of a 1-D space-variant processor.[7,8] In this recording scheme, the intensity of the sum of the filtered signal and an on-axis reference beam is integrated by a charge-coupled device (CCD) array. The bias term is subsequently removed electrically, yielding the desired signal term with amplitude and phase information preserved. Though some problems were encountered due to a spatially-varying CCD array response, we believe these problems can be solved. One related result of interest is the ability of the processor to simulate the performance of parametric amplifiers. Experimental results were obtained demonstrating both space-invariant and space-variant applications. A Hilbert transform processor and a bandpass filter were two of the applications which were successfully demonstrated.

3. Architectures for Optical Binary Multiplication

The main goal of this project was to apply optical space-variant processing techniques to the area of discrete numerical computations, primarily binary arithmetic. The particular problem of implementing binary multiplication was chosen because it contains the major operations required of a computer's arithmetic logic unit.

Our initial approach of color-encoding the multiplier data and using feedback to convert from mixed binary to binary format[9,10] was then found to require too many passes through the Hughes Liquid Crystal Light Valve and was consequently too slow. A new approach was taken which first forms all the partial products simultaneously in parallel.[11,12] We then regroup the bit products thereby obviating the necessity of the "shift" operation. Finally, we optically perform carry look-ahead addition of the resulting binary words to get the final product. The number of intensity levels is restricted to three, as before, preserving the noise immunity and thus providing high accuracy. The multiplier and multiplicand bits, encoded in bright true logic, are introduced in bar-shaped patterns onto the WRITE and READ sides of a Hughes LCLV. The analyzer is kept crossed with respect to the direction of polarization of the incoming beam. The AND operation performed results in the formation of an array of partial products. The bit products are then regrouped diagonally to form new binary words. Entire partial products need no longer be shifted in this case. These binary words are then added to get the final product. An algorithm for optical carry look-ahead addition was conceived, and implemented in an optical arrangement which produces all the carries in essentially one switching time. Proof-of-principle experiments were conducted to (a) form the array of partial products and (b)generate the carries. These experiments confirmed the validity of the new techniques. The proposed system offers a better solution to the problem of the propagation of carries than earlier approaches utilizing residue arithmetic. It performs a multiplication in only 13 switching times of the LCLV. It utilizes the spatial parallelism of optical systems to perform a number of multiplications and additions in parallel, and thus could become the processing unit of a very fast optical matrix multiplier. To illustrate the speed of the architecture developed, if the basic response time of the LCLV were 20 μsec rather than 20 ms, the system could be capable of performing approximately 4 million 8-bit multiplications per second.

We also discussed techniques by which this fast optical multiplication architecture could perform real time matrix-vector multiplication, thus widening its range of applicability to linear algebra processors. In summary, we firmly believe that with the advent of even faster spatial light modulators, this very fast optical binary multiplication architecture will generate even wider interest than that generated to date.

4. Bilinear Optical Processing and Applications.

A. Introduction

During this funding period, we have investigated extensions of our previous space-variant work to the new area of 2-D nonlinear space-variant processing. In particular, we concentrated on potential applications in the area of optical computing. As a start, we investigated the simplest nonlinear system, i.e. the bilinear space-variant system. As a result, a general mathematical model was developed,[13,14] several optical implementation techniques were designed, and a number of application areas were studied.[15-21,24,27,28]

B. Mathematical Formulation

A 1-D bilinear space-variant operation can be described by

$$g(y) = \int\int_{-\infty}^{\infty} h(y;x',x'')\, f'(x')\, f''(x'')\, dx'\, dx'',$$

where f' and f" are two inputs, g is the output and h is the kernel of the system. This equation is also known as the bilinear transform. A characteristic of this transform is that if one of the inputs is fixed, then the transform becomes a generalized linear transform. The properties of this bilinear operator have been studied, resulting in a new set of space-variant system classifications. This added "richness" to the class of space-variant systems gives rise to new implementations and applications in the area of optical computing.[13]

C. Implementations

(1) Using 2-D linear space-variant processors.

We have shown that if we use the output of a 2-D linear space-variant processor which lies on a 45° line with respect to both output axes, change the 4-D kernel into 3-D kernel and apply two inputs on the orthogonal axes of the input plane, a 1-D bilinear transform is realizable.

(2) Phase grating technique with a liquid crystal light valve (LCLV).

By using LEDS (input f"(x")) at different locations, each LED can produce a different spatial grating on the "WRITE" side of an

LCLV (if a reference beam is added). Based on performing the AND operation on the LCLV, the input $f'(x')$ on the "READ" side of the LCLV will be imaged at different output locations where we place different space-variant holograms (e.g. multifaceted holograms). In this way a 2-D bilinear transform is achievable.[13]

(3) Acoustooptical processor

Consider the light incident on an acoustooptic cell as the first input $f'(x')$, and the electronic signal input to the acoustooptic cell as the second input, $f''(x'')$. By frequency modulation and spatial modulation of the acoustooptic cell, any combinations of two inputs will be deflected to different output locations where holograms (kernels) are placed. With this system a 1-D real-time bilinear transform can be performed.[15] Using a multichannel acoustooptic cell will improve the space-bandwidth product requirements.

D. Applications

A bilinear transform in discrete form can be represented by a triple vector-matrix-vector product, i.e.

$$g(y) = \sum_{n=1}^{N} \sum_{n=1}^{M} f'(n)\ h(y;n,m)\ f''(m)$$

$$= \underline{f}'^{T}\ H\ \underline{f}''$$

where H is a matrix, $\underline{f}'$ and $\underline{f}''$ are two column vectors and T represents the transpose operator. The following applications all use this discrete formulation of the bilinear transform.

(1) Programmable optical interconnections.[16]

By using f" as a control input and f' as a signal input, the bilinear transform can be made to perform programmable optical interconnections. By changing the control input, the system can provide various mappings between signal input and output. This approach offers a great flexibility in logic design, since tens or hundreds of operations can be performed using a fixed system.

(2) 2-D Cross-bar[17]

Let H be a 2-D input, and let f' and f" be two control inputs in the two orthogonal dimensions, respectively. By changing the control inputs, each entry of H can be mapped to different locations in a 2-D output plane. Furthermore, a 2-D crossbar can be performed in real time if real-time SLMs(such as the magnetooptic (LIGHT-MOD) are used to replace the two control inputs f' and f".

(3) Triple-product processing

The discrete bilinear transform can be extended to triple matrix-matrix-matrix products, i.e., $g(y) = F' H F''$. Here F', F", and H are all considered signal inputs. This triple product processing is useful in image processing. It can also be used to implement a generalized eigensystem if feedback is considered.

Secondly, we can use triple-product processing to implement logic designs for either combinatorial or sequential circuits. This processor can also operate in an MIMD (multiple instruction multiple data) format.[18]

(4) Bilinear 2-D space-variant processing[19]

A generalized discrete 1-D optical processor with a 2-D kernel can be viewed as a matrix-vector multiplier. Since most of the data processed in optics are 2-D, we investigated a generalized 2-D processor which has a 4-D kernel. This processor can compute the output in one time step given the entire input data, which is in contrast with a regular systolic array which accepts time-serial input data and accumulates the output over many time steps.

To explain the 2-D operations, we introduced the mathematical concepts of 2-D vectors, 2-D matrices, and operations such as a 2-D inner product, outer product, matrix-vector multiplication, and matrix-matrix multiplication. Based on these concepts, we constructed two types of 2-D discrete optical processors, i.e., direct processors and back-projection processors. Two specific applications were investigated. A 2-D version of the Hopfield neural net'ork was developed which is able to perform 2-D neural operations. Also, combining the 1-D outer product operation and a 2-D data format, the standard matrix-matrix multiplication operation was shown to be easily implemented in one time step.

(5) Optical polynomial processing[20,21]

With the motivation of extending bilinear operators to a more general class of nonlinear operators via a Volterra series (polynomial) approximation, optical polynomial processors[22,23] with high speed and throughput need to be investigated and implemented. We examined optical polynomial implementations using a factored representation so that the bilinear techniques developed under this funding can be employed. Since there are two inputs and one kernel in the generalized bilinear transform, the two inputs act as polynomial input variables and the elements in the kernel represent the coefficients of the quadratic polynomial. Thus higher order polynomial processing can be realized by iterating the bilinear transform.

A dual-LCLV system has been set up to form such a quadratic polynomial. Using electronic or optical feedback, a general optical polynomial processor is achievable. The work has been extended to perform bipolar complex analog and binary digital polynomial operations. The analog operations can be performed by using separate parallel channels for real/imaginary and positive/negative numbers. The concepts of systolic and wavefront processing can be used to implement binary digital polynomial processing. The polynomial system for digital processing has been set up and tested in the lab with good results.

(6) Window-Programmable Image Processors[13]

To solve the problem of implementing high speed processing of large amounts of data, such as 2-D or 3-D images, present electronic computers are limited due to their fundamentally serial nature. One approach to overcoming this problem is to use optical computing systems with the capabilities of parallel, high speed processing.

We designed an optical system, based on the bilinear transform, for processing 2-D images. In the area of linear, space-invariant image processing, the output images can generally be expressed as the convolutions of the input images and small window functions. In other words, the output image is equal to the summation of the shifted input images which correspond to the weights and locations of coefficients in the window. If we interpret one of the inputs in the bilinear transform as an input image, the other one as a window and the kernel as shift gratings, then a convolution-based image processor can be looked at as a bilinear processor. Experimental results were obtained demonstrating bipolar two-level image processing where edge-enhancement was the application which was successfully demonstrated.

(7) Optical Multistage Interconnection Networks.[24]

This project was motivated by our 2-D optical crossbar implementations. Recently, a number of optical interconnection networks have been proposed and demonstrated such as crossbar networks[25] and perfect shuffle networks.[26] In spite of their feasibility, however, these networks only deal with 1-D data and ignore the inherent 3-D characteristics of optical systems. Another major problem is that although crossbars are ideal networks for interconnections, crossbar networks of large size are very difficult to implement either in optics or electronics. An alternate approach is to design multistage networks, with each stage having a number of crossbars of small size. Based on the above noted reasons, we believe the continued investigation of 2-D optical multistage interconnection networks (MINs) is very important.

We have proposed the framework of a 2-D MIN and explored the advantages and applications of the 2-D perfect shuffle network, including (1) the quaternary number representation of the 2-D perfect shuffle network, (2) reduction of the number of stages for realizing all permutations between inputs and outputs, (3) implementation of a 2-D FFT, (4) bivariate polynomial evaluation and (5) matrix transposition. Also an experimental setup for a 2-D perfect shuffle demonstrated the simplicity of an optical implementation. We are definitely encouraged by the results obtained to date on this particular project and we believe that the further investigation of the 2-D MIN is of great interest in the field of optical computing.

(8) A 2-D Clos Optical Interconnection Network.[27,28]

The interest in devising a 2-D Clos network is due to its 3-stage layout and ability to implement 2-D crossbar networks of large size using a number of subcrossbars of medium size. The Clos network has the same characteristics as the crossbar network, but an important factor is that the number of switching elements has been reduced in the Clos network (10:1 for a 1000x1000 network, as compared with the crossbar network). The difficulty of determining routing connections, however, is a major problem to be overcome.[29] We have come up with a straightforward algorithm to route the Clos network. This algorithm can be performed either by a uniprocessor or by parallel processors. Also the routing algorithm is not unique, and the possibility for alternative choices gives the routing algorithm an ability to tolerate faults. We have demonstrated an optical implementation of the 2-D Clos network with good experimental results. A 2-D Clos network can also be used to realize 2-D neural networks, and furthermore, the neural connections are programmable. This will give neural processors the flexibility to perform more complex computations.

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RESEARCH PERSONNEL (1984-1987)

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RECORD OF JOURNAL PUBLICATIONS ON AFOSR 84-0382*

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1. V. Chandran, T.F. Krile, and J.F. Walkup, "Optical Techniques for Real-Time Binary Multiplication," Appl. Opt. 25, 2272-2276 (1986). Feature issue on Optical Computing: Part 2.

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1. S.H. Lin, T.F. Krile, and J.F. Walkup, "A 2-D Optical Clos Interconnection Network and Its Applications," (to appear in feature issue of Applied Optics on 1987 Lake Tahoe Topical Meeting on Optical Computing, 1988).

Journal Article in Preparation

1. S.H. Lin, T.F. Krile, and J.F. Walkup, "A Generalized Bilinear Transform," (to be submitted to J. Opt. Soc. Am. A.).

Scientific Report

1. S.H. Lin, "Optical Processing Based on the Bilinear Transform," Scientific Report AFOSR-84-0382-1, Optical Systems Laboratory, Texas Tech University, 150 pp., Aug. 1987

* Paper appearing in published conference proceedings listed under "Interaction Activities."

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8. T.F. Krile and J.F. Walkup, "Optical Systems Research at Texas Tech University," SPIE Proc. 634, 457-474, Workshop on Opt. and Hybrid Computing, Leesburg, VA, March 1986.

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10. S.H. Lin, T.F. Krile, and J.F. Walkup, "Optical Polynomial Processing Based on the Bilinear Transform," J. Opt. Soc. Am. A3, 13, p. 96 (1986). (Paper presented at 1986 Annual Meeting, Opt. Soc. Am., Seattle, WA, October 1986).

11. S.H. Lin, T.F. Krile, and J.F. Walkup, "2-D Optical Multistage Interconnection Networks," SPIE Proc. 752, O-E LASE'87, Los Angeles, CA, January 1987.

12. S.H. Lin, T.F. Krile, and J.F. Walkup, "A 2-D Clos Optical Interconnection Network," OSA Top. Mtg. on Opt. Comp., Incline Village, NE, March 1987.

13. S.H. Lin, T.F. Krile, and J.F. Walkup, "Optical Polynomial Vector Processing," Proc. 14th Congress of Int. Comm. for Optics, 483-484, Quebec, Canada, August 1987.

14. S.H. Lin, T.F. Krile, and J.F. Walkup, "A Generalized Discrete 2-D Optical Processor." (Paper presented at 1987 Annual Meeting, Optical Society of America, Rochester, NY, October 1987).

15. S.H. Lin, T.F. Krile and J.F. Walkup, "Electro-Optical Implementations of Programmable Quadratic Neural Networks," O-E LASE'88, Los Angeles, CA, January 1988.

Other Significant Interaction Activities:

1. Laboratory visits to Stanford University, U.C.-San Diego, U. of Washington (J.F. Walkup and/or T.F. Krile).

2. Breifings of Dr. Lee Giles in Washington, D.C. (J.F. Walkup).

3. Chairman of IEEE Computer Society Technical Committee on Optical Processing, 1984-1986 (J.F. Walkup).

4. Served on Education Committee, Optical Society of America, 1984-1986 (J.F. Walkup).

5. Chairman, Education Council, Optical Society of America, 1987-1988, and member of OSA Board of Directors (J.F. Walkup).

6. Attended 1987 Gordon Conference on Optical Information Processing and Holography, Santa Barbara. Elected as Vice-Chairman of 1988 Gordon Conference (J.F. Walkup).

SIGNIFICANT ACCOMPLISHMENTS

1. Developed an improved measure of the degree of invariance of linear optical systems.

2. Developed a real-time holographic CCD recording technique for preserving phase information when using intensity-sensitive detectors.

3. Investigated and implemented a fast, highly parallel architecture for optical multiplication of binary numbers.

4. Developed techniques for programmable optical interconnections based on the bilinear transformation.

5. Developed an optical 2-D Clos interconnection network. Demonstrated significant advantages of this type of multistage interconnection network as compared to crossbar networks.

6. Investigated optical polynomial processors and their applications in areas such as polynomial neural networks.

7. Investigated an optical triple-product processor based on a generalization of the bilinear transform. Examined applications including a 2-D optical cross-bar switch and implementations of combinational and sequential logic.

8. A complete theory of the generalized bilinear transform was developed and many properties of bilinear systems were examined.

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